HYDROGEOLOGICAL RISK SCREENING FOR UNCONVENTIONAL OIL AND GAS DEVELOPMENT

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Abstract

With the pace of change in the Unconventional Oil and Gas (UCOG) industry occurring so rapidly (particularly in the field of shale gas) there are a large number of stakeholders who need to understand how this may impact upon them. The planning and permitting process provides the formal process for applications whereby effects are identified and impacts on receptors are assessed and managed. However, many stakeholders will wish proactively to assess the risks to them and their assets in advance of the submission of applications.

This paper looks specifically at the potential impacts of UCOG on the water industry and a method for high level screening of risk to their assets. Whilst focussing on UCOG, elements of the approach are applicable to other extractive industries. The approach uses the well-established source-pathway-receptor model to identify where receptors may be impacted. For UCOG, the source will be where potential contaminants are introduced or stored; the pathway will be the aquifer or watercourses; and the receptors for this particular study will be abstraction and treatment points. The main impacts are on resource quality, resource availability and wastewater treatment capacity and capability.

The screening is Geographic Information System (GIS)-based and utilises freely available open source GIS software (QGIS/GRASS) and scripting (Python) to process spatial data. An increasing number of spatial datasets are becoming freely available. These include Petroleum Exploration Development Licence (PEDL) data and exploratory well locations along with associated background databases. Other datasets are commercially available, such as the BGS (British Geological Survey) 3-D lithoframe model (BGS, 2014) and planning application data.

By identifying risk factors, using the GIS model to process them, and assigning risk scores and criticality ratings to various receptors, the approach allows a high level risk screening of assets to be carried out. This can be refined as risks become better understood and new datasets become available. The same methodology may also be applicable during the search for future aggregate extraction sites.

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Introduction

An increasing amount of spatial data are becoming more readily available and cheaper to obtain. A similar situation is also true for the tools that are used to analyse the data, with open source GIS software and applications frequently rivalling commercial counterparts.

One potential use for these data and tools is in the screening of risk relating to development. This could be any development where spatial data can be used to determine risk. An example is presented in this paper of the way spatial data and open source tools have been used to assess the potential risk of Unconventional Oil and Gas (UCOG) development on Severn Trent Water Limited (STWL) groundwater and surface water abstractions (sources). It is stressed, however, that this example is used to illustrate the potential of the approach in general – it could be used for other applications such as the impact of quarry operations on nearby receptors.

For STWL it was important to have an early conceptual understanding of the risks of UCOG development. They operate a large number of groundwater and surface water abstractions that together form the public water supply to much of central England. UCOG development uses water and produces wastewater and takes place not only on the surface within the surface water catchments that feed surface water abstractions, but also through the Principal Aquifers which are used for water supply.

The term 'risk' is used throughout this paper; however, the risks to STWL's assets will be managed through the regulatory and planning process, so the term is used more to denote a relative ranking which would allow appropriate focus of attention and resources. It should not be taken to indicate that any of STWL's assets or the security of the water they supply are considered to be in danger of being compromised in any way.

What Is Unconventional Oil And Gas (Ucog)?

Unconventional sources of oil and gas are defined as those geological formations from which oil and gas are obtained by means other than conventional methods (where hydrocarbons flow freely to, or are pumped from, a well). They include the following main types:

- Gas shales
- Underground Coal Gasification (UCG)
- Coal Bed Methane (CBM)
- Tight gas sands
- Coal Mine Methane (CMM)
- Abandoned Mine Methane (AMM)

This paper focuses on the first three listed (gas shales, UCG and CBM) as these are the most relevant in STWL's combined water and wastewater area (the study area). A brief description of these types of UCOG development is provided below.

Gas shales (Fracking)

This involves drilling a vertical borehole at surface that deviates to the horizontal at the target depth at which fracking is to take place (Figure 1). The well casing is then perforated in the fracked section. Fracking fluid is injected at pressure sufficient to hydrofracture the rock surrounding the perforated section. The fluid is predominantly water but also contains a number of additives which assist the process, along with proppant (frequently sand) which is carried into the fractures and holds them open once the pressure is reduced. Flowback of fracking fluid and some formation water occurs following pressure relief, and gas, formerly trapped within the formation, is released and migrates through the newly-formed fractures. Active pumping occurs following pressure relief with the proportion of fracking fluid in the produced water steadily reducing over time and gas continuing to be released. There is the risk of frack fluid, flowback water, produced water, and gas migration which could result in receptor contamination, as well as induced seismicity.

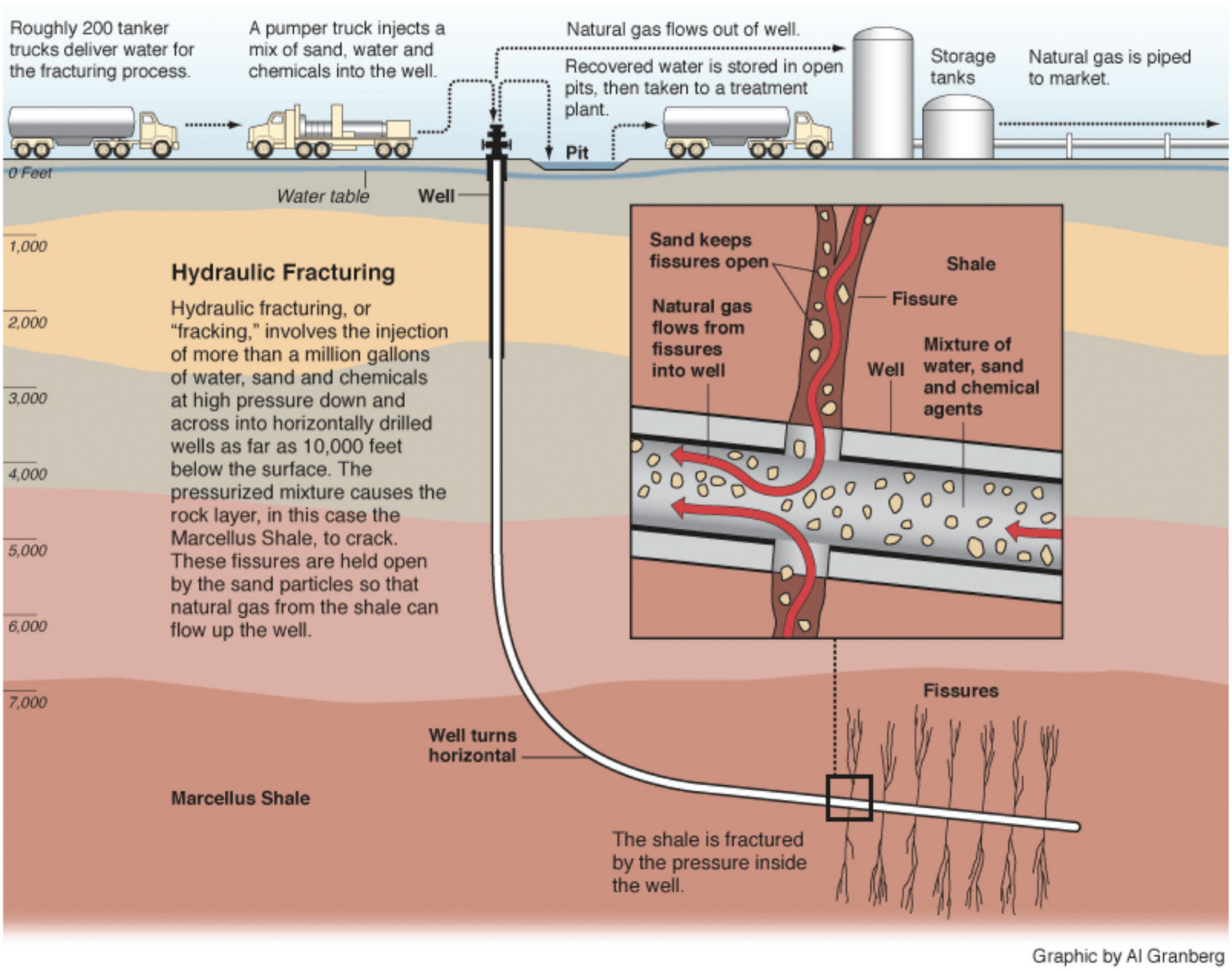

Figure 1. *Schematic of shale gas/fracking process – US example (image courtesy of Al Granberg/ProPublica (ProPublica, 2016).*

Underground Coal Gasification (UCG)

In this process injection and abstraction wells are constructed down to a target coal seam. An oxidiser is injected down the injection well and drawn towards the abstraction well. The presence of the oxidiser results in a partial, controlled combustion of the coal seam between the wells, and a release of gas which is abstracted to the surface (Figure 2). The process generates heat and combustion by-products and also results in loss of rock volume where combustion has taken place. There is the potential for the migration of combustion by-product contaminants (enhanced by the heat generated) and subsidence due to the loss in rock volume.

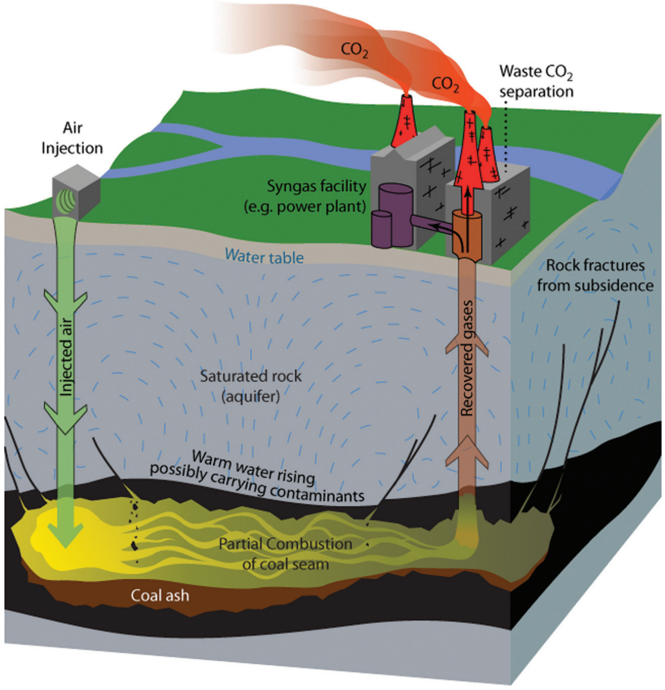

Figure 2. *Schematic of the UCG process (image courtesy of Bretwood Higman, Ground Truth Trekking (Ground Truth Trekking, 2010).*

Coal Bed Methane (CBM)

Methane can occur within coal seams adsorbed to surfaces within pores and fractures. In a CBM operation a well is drilled to the target seam and the pressure is reduced by pumping. The pressure reduction causes the adsorbed gas to be released and to flow, along with formation water, toward and out of the abstraction well (Figure 3). Hydrofracturing, like that employed for shale gas, is sometimes used to enhance the flow of gas.

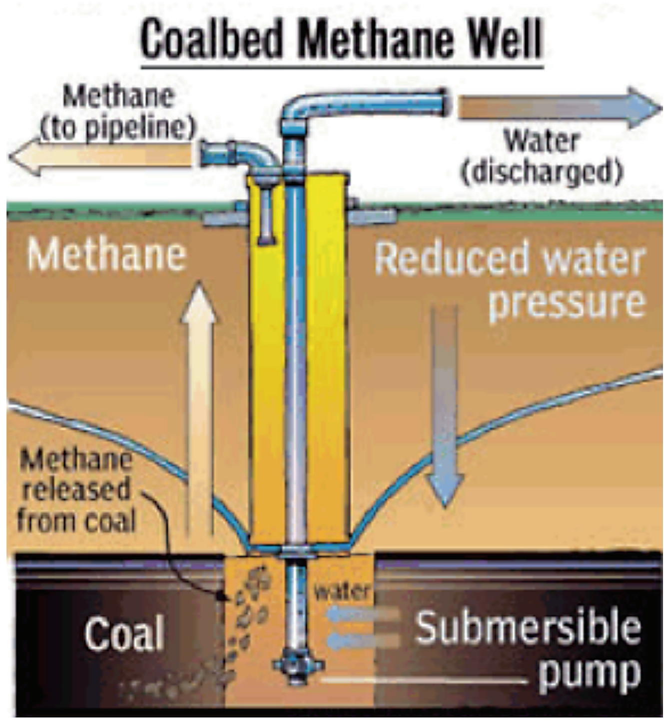

Figure 3. *Schematic of CBM process (image courtesy of Frost and Sullivan Market Insight (2002)).*

The Current Planning And Regulatory Process

Legislation

On-shore (landward) exploration of hydrocarbons in the UK is governed by the Petroleum Act 1998 which supersedes the Petroleum (Production) Act 1934.

The Petroleum Act 1998 vests all rights to the nation's petroleum resources in the Crown. The Government can grant licences that confer exclusive rights to 'search and bore for and get' petroleum. Each licence confers such rights over a limited area and for a limited period. The Petroleum Act 1998 defines 'Petroleum' to mean: 'any mineral oil or relative hydrocarbon and natural gas existing in its natural condition in strata excluding coal or bituminous shales or other stratified deposits from which oil can be extracted by destructive distillation.'

Licence types

On-shore (landward) licences are granted by the Department of Energy and Climate Change (DECC).

Until 1996, the government issued a sequence of separate licences for each stage of an onshore field's life. These licences took a number of difference names. Since 1996 all on-shore Petroleum licences have been issued in the form of Petroleum Exploration and Development Licences (PEDL). For licences issued prior to 1996, the licences remain named as per their original nomenclature, however they can all be considered as PEDLs under the Petroleum Licencing Act 1998.

PEDLs are the present type of landward licence. Applicants must prove technical competence, awareness of environmental issues, and financial capacity before an offer of a PEDL will be made. A number of non-conventional energy sources are regulated under the Petroleum Act 1998. These include:

- Shale gas
- Coal-bed methane

It should be noted that Underground Coal Gasification (UCG) is not covered under a PEDL but, instead, is licensed under the Coal Industry Act 1994 (Anon, 1994).

Each PEDL carries an annual rental and is valid for a sequence of terms. These terms are designed to follow the typical lifecycle of a field: exploration, appraisal, and production. The respective duration of each term is six years, five years, and 20 years.

The rights granted by landward licences (PEDL) do not include any rights of access, and the licensees must also obtain any consent under current legislation, including planning permissions from relevant local authorities and environmental approvals from the Environment Agency in England; the Scottish Environmental Protection Agency (SEPA) in Scotland; Natural Resources Wales in Wales; and Northern Ireland Environment Agency in Northern Ireland. It should be noted that licensees wishing to enter or drill through coal seams must also seek the permission of the Coal Authority in addition to obtaining an appropriate PEDL and appropriate consents from environmental regulators and local authorities.

Based on the definition of Petroleum given by the Petroleum Act 1998, licences (PEDL) do not specify the nature of the hydrocarbon activity as the licence permits extend to 'any mineral oil or relative hydrocarbon and natural gas existing in its natural condition in strata'. This may therefore include conventional oil & gas reserves and unconventional reserves such as shale gas and CBM.

Onshore licensing rounds

DECC issues licences through competitive licensing rounds. For DECC's oil and gas licensing purposes, exploration and development areas are divided into 10x10km squares, each one being referred to as a block. A licence may cover a whole block, part of a block, or several blocks or part-blocks.

The first on-shore licencing round was in 1986, although onshore exploration and development of oil and gas had been undertaken as far back as the 1850s. The most recently completed, the 13th on-shore licencing round, was held in 2008. Following closure of that application period, the Government issued 93 new PEDLs to 54 companies. In addition to conventional oil and gas exploration, 20 of these applications were for CBM and others for mines gas (AMM or CMM, where methane is extracted from existing mines) and shale gas.

In 2010, DECC published and consulted on a Strategic Environmental Assessment (SEA) in preparation for the 14th onshore licensing round (DECC, 2010) which is currently underway; this process was suspended following the seismic tremors recorded during hydraulic fracturing operations at Preese Hall in Lancashire but has subsequently resumed. In December 2013 DECC published, for consultation, an Environmental Report on proposals for further onshore oil and gas licensing in areas of Great Britain (DECC, 2013). This is a necessary part of the SEA process. The Report was open for public consultation until 28 March 2014. Figure 4 shows the SEA areas and the licensed blocks for the UK as of the 1st May 2014 with STWL supply area.

A summary of the planning and legislative process to achieve exploratory well testing is shown in Figure 5, and from exploratory well testing to commercial development in Figure 6.

Assessing Risk Case Study – Severn Trent Water

Conceptual understanding of risks to surface water and groundwater

Risk from unconventional oil & gas development to STWL assets may arise in three ways:

1. The likelihood of underground fluids (including gas, deep formation groundwater below the main aquifer and fracking fluids) from unconventional sources of gas (shale gas, UCG and CBM) migrating towards STWL assets (groundwater abstractions and surface water abstractions) (Figure 7). The likelihood of migration will depend on many risk factors including the thickness of lithology between the aquifer and the asset, the number of oil & gas wells in a Source Protection Zone (SPZ), the number of geological faults, etc.
2. The ability/capacity of STWL Wastewater Treatment Works (WWTWs) to take and process wastewater from UCOG development.
3. Depletion of available water resources as a result of fracking process water use.

The risk from development to STWLs assets will increase over time as more development takes place and will be controlled by both the PEDL licensing regime and the planning and permitting regime that controls the individual drilling sites. The current 13th PEDL round covers a limited area of the STWL north-east region (Figure 8). However, the 14th round area (also Figure 8), for which applications are currently being assessed, covers a much greater proportion of the combined STWL water supply –sewage area.

Risk to water resource quantity

The risk to the water resource quantity for STWL is related to the requirement of UCOG exploration and development to use significant amounts of water, mainly for the fracking operations that occur both during the initial drilling phases of a well and during its lifetime. The amount of water required in any one area will depend on the number of pads per unit area of land and the number of wells drilled at every pad (Stone et al, 2013). The operator can source water either from the local aquifer or from local water companies.

The SEA for the 14th Round identified that, on the conservative assumption that each well is re-fracked once in its lifetime, total water consumption associated with hydraulic fracturing could be between 57.6 million to 144 million cubic metres under a high activity scenario. In that scenario, annual water use could be up to 9 million cubic metres, which would be approximately 18% of the 48.5 million cubic metres of mains water presently supplied to the energy, water, and waste sectors annually. The potential impacts that this could have on, for example, water resource availability, aquatic habitats and ecosystems and water quality is, however, more uncertain. Water would typically be sourced from a mains water supply which would need agreement from the relevant water company, or could be abstracted from groundwater or surface water which would need an abstraction licence. In either case, any addition to demand would only be granted where assessed by the regulator as sustainable. Demand could however be

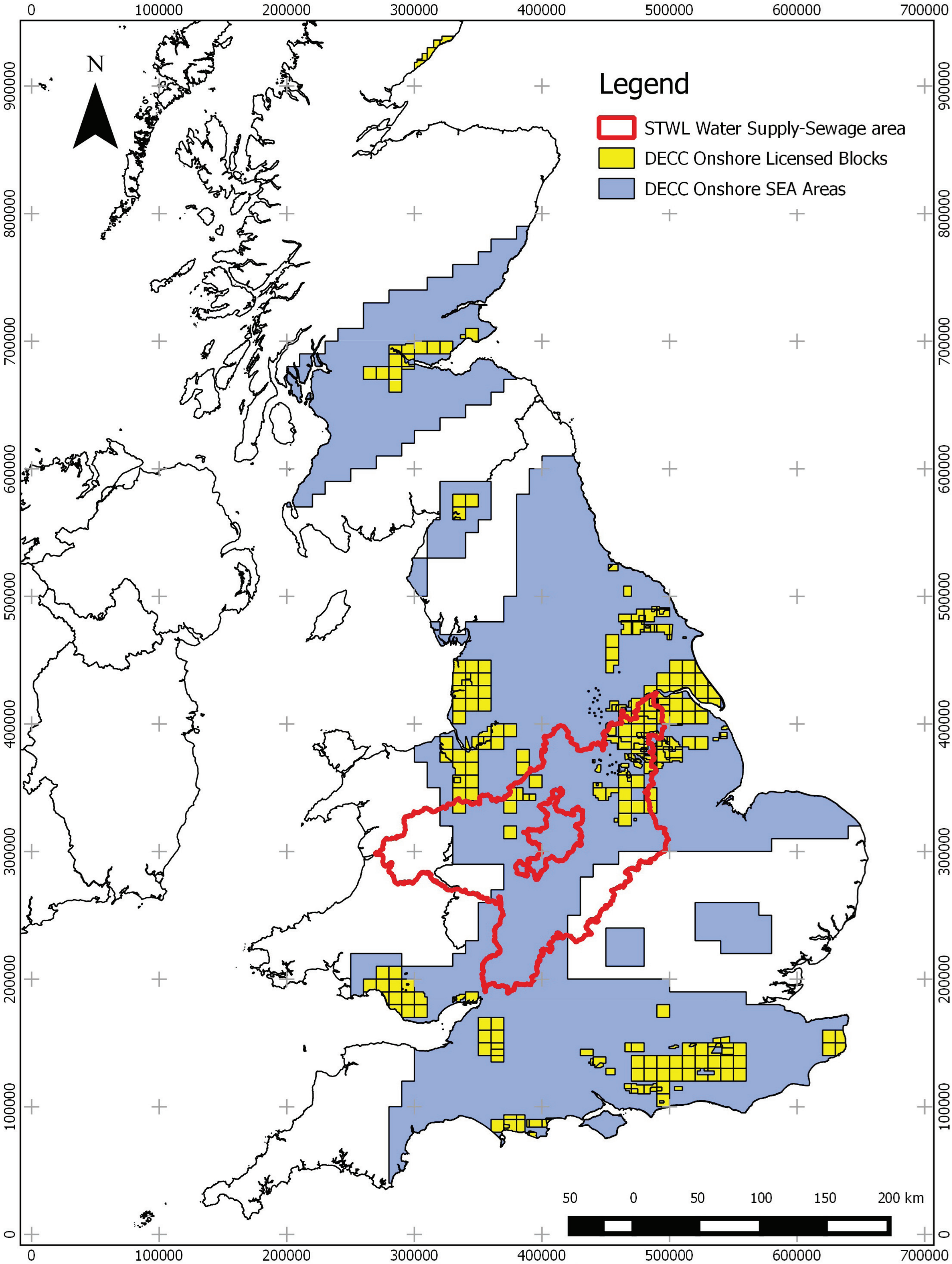

Figure 4. *Strategic Environmental Assessment (SEA) areas and licensed areas for the 14th Round.*

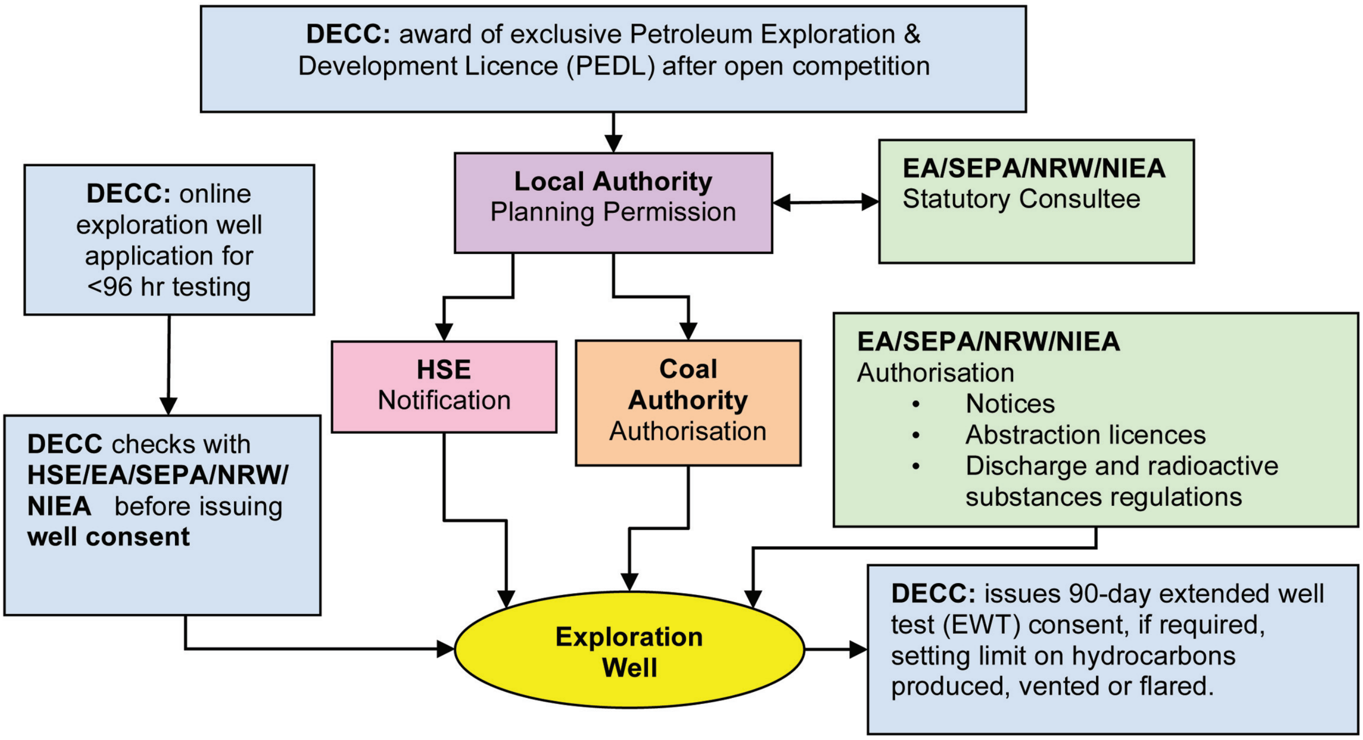

Figure 5. *Flow chart showing the key planning and regulatory steps to achieve exploratory well testing.*

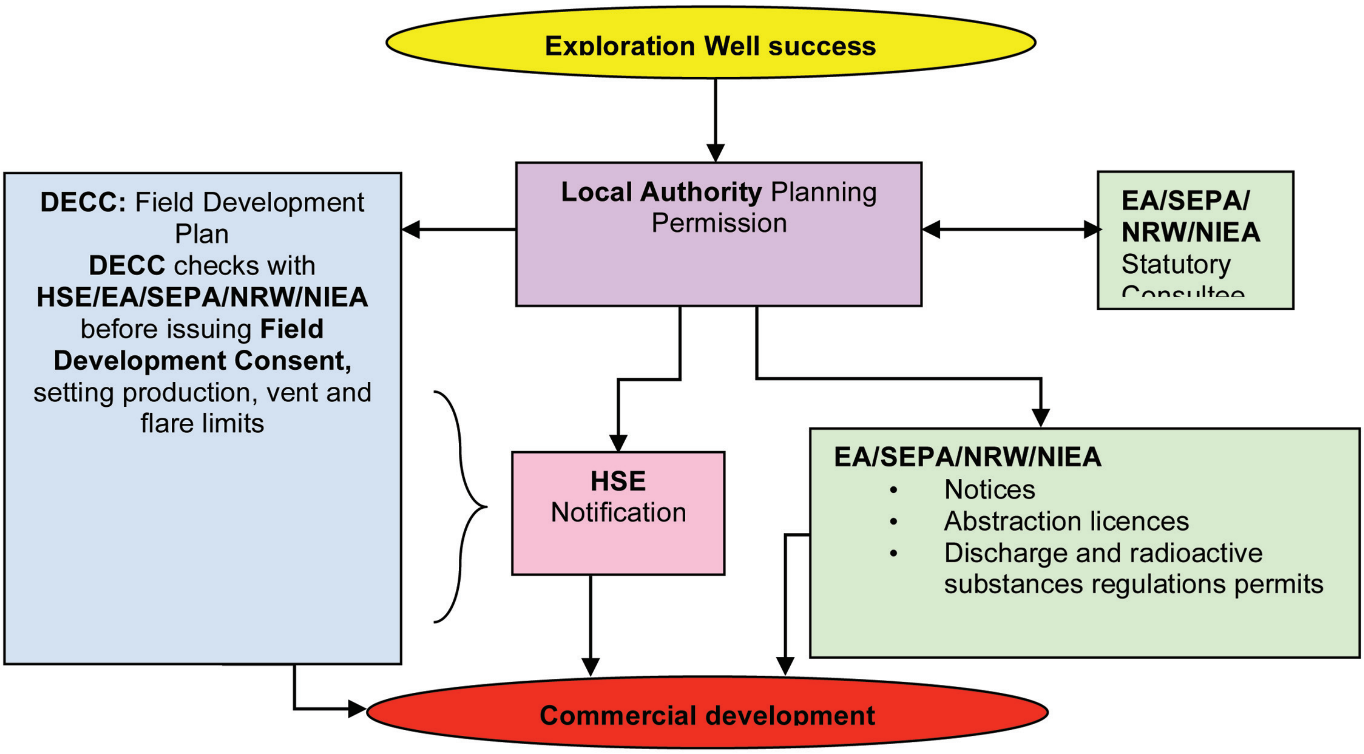

Figure 6. *Flow chart showing the key planning and regulatory steps from exploratory well testing to commercial development.*

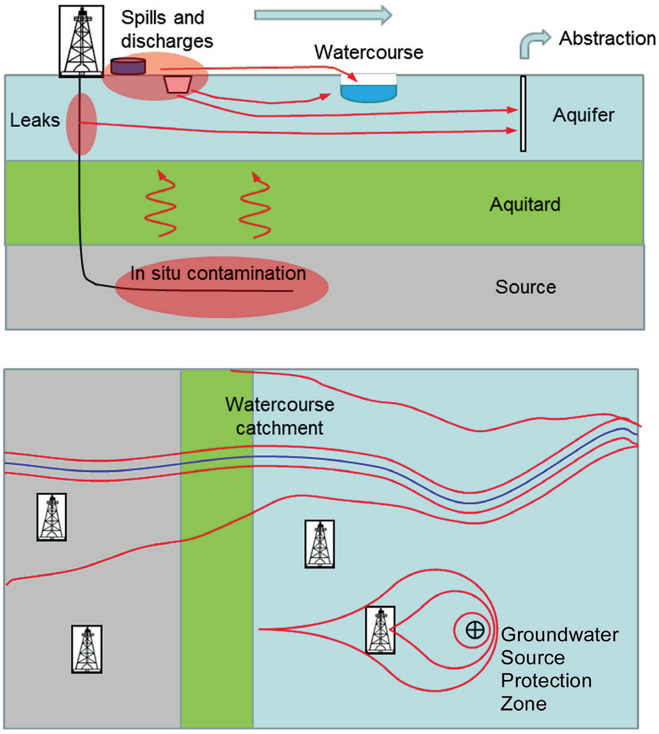

Figure 7. *Simplified representation of the key conceptual components of risks to surface water and groundwater.*

substantially reduced if it could be met from recycling and reuse of flowback water.

Risk to water resource quality

The risk to water quality will vary depending on whether a groundwater abstraction or a surface water abstraction is considered. This difference is due to the different pathways that the potential contaminants may follow.

The following could occur:

- Groundwater: Potential contaminants could make their way to the aquifer either through surface spillages or via vertical upward migration from the unconventional source (either through geological faults, poorly completed wells, etc.) and would be abstracted by boreholes at STWL's groundwater sources.
- Surface Water: Potential contaminants could be abstracted at STWL surface water abstraction sites if these are downstream of STWL's STW discharges. Equally, contaminants could reach the surface water abstraction site if fracking fluid entered the watercourse either via surface drainage following a spill event or via groundwater-surface water connection should the groundwater be contaminated.

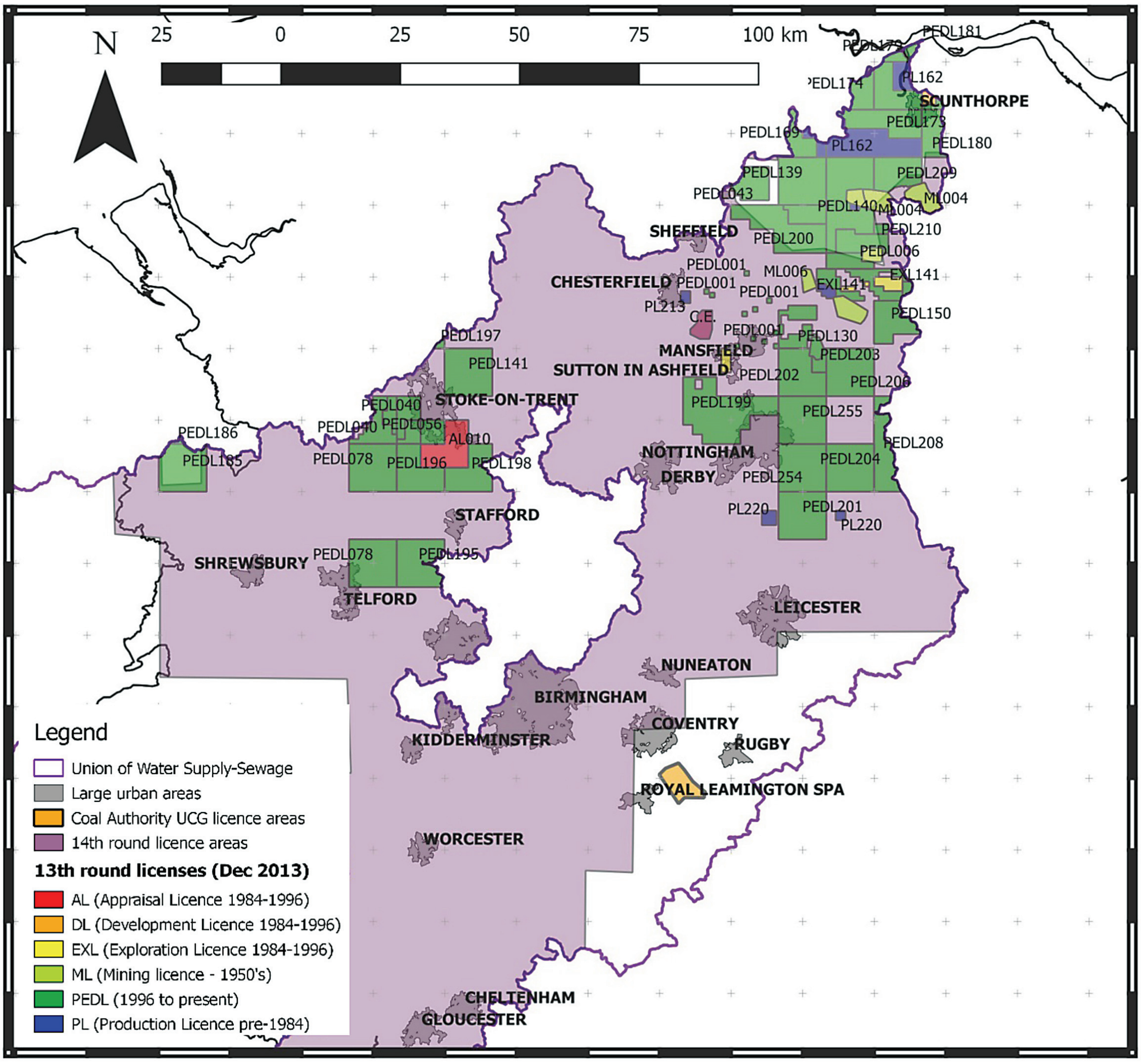

Figure 8. *Map showing PEDL licence areas within the north-east STWL area. (The boundary of the STWL area is described in the legend as 'Union of water supply-sewage').*

Key factors in assessing risk

Geology

The geology of the STWL combined water supply and sewage area is shown on Figure 9. In terms of outcrop, the area is dominated by Permo-Triassic rocks (sandstones and mudstones) which occupy much of the central part of the area and are the main aquifer for water supply. Along the eastern boundary Triassic-Jurassic Lias Group rocks (mudstone, sandstone, siltstone and limestone) outcrop. In an area to the north of Stoke on Trent, Derby and Nottingham, Carboniferous rocks, mainly comprising Millstone Grit and Coal Measures, crop out. Smaller outcrops of Carboniferous strata also occur between Birmingham and Wolverhampton, between Birmingham and Coventry, and along the western outcrop edge of the main Permo-Triassic outcrop. It is the Carboniferous units beneath the Millstone Grit (and Permo-Triassic aquifer) that are the main focus of UCOG development. In the western part of the area going into Wales, older rocks, principally Ordovician, Silurian, and Devonian crop out. These strata are found either at outcrop or at depth across a large proportion of the area. Cambrian rocks have also been suggested as potential shale gas source rocks but there is little information on their prospectivity (Stone et al, 2013).

Source Criticality

As well as the risk to the potable water assets, the criticality of that asset to STWL within the water supply network also needs to be taken into account. The STWL assigned criticality grades represent the strategic criticality of the whole site in terms of population served and the availability of alternative sources. Criticality assessments were carried out under normal demand conditions for active supply boreholes. The criticality grades, resulting from the assessments reflect the as-is position and do not take account of any unconfirmed future schemes that may otherwise permanently reduce or increase the criticality of that source. The criticality grades and the relative definitions are listed in Table 1.

Criticality Grade	Impact if lost
1	20,000+ people affected
2	<20,000 people affected
3	No one affected but dependency created on a site that would affect 20,000+ if lost
4	No one affected but dependency created on a site that would affect <20,000 people
5	No one and no dependency
6	Not part of active network

Table 1. *Definition of STWL source criticality grades.*

Surface water catchments

Assessing the risk to potable surface water infrastructure is complex as there are several factors that contribute, to different degrees, to the overall risk. Many of STWL's Water Treatment Works (WTWs, as distinct from WasteWater Treatment Works - WWTWs) source

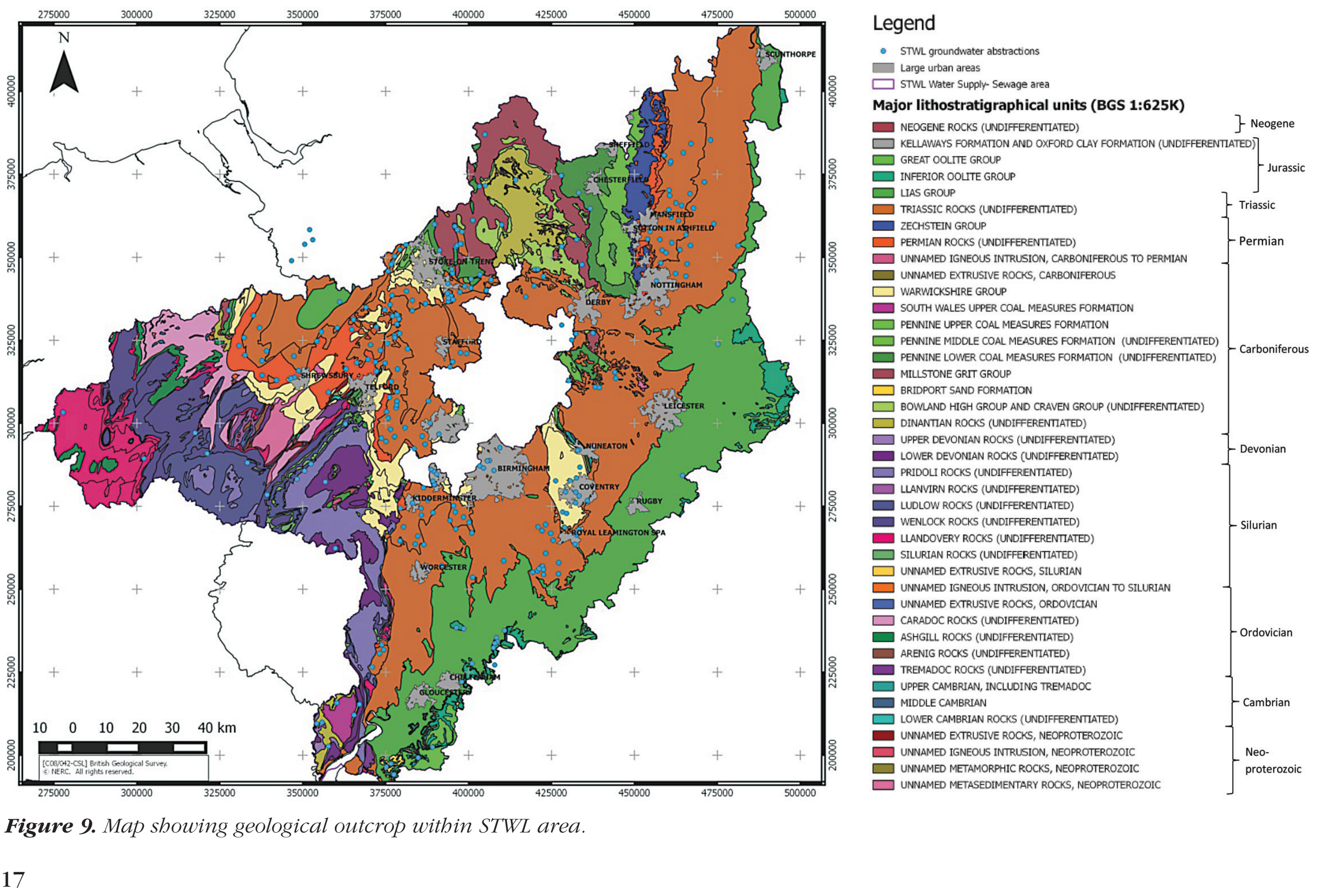

Figure 9. *Map showing geological outcrop within STWL area.*

their water from several abstraction points. These often lie in different catchments (e.g. the Whitacre WTW abstracts its water from both the River Blythe and the River Bourne catchments, with the former supplying most of the potable water to the WTWs). For each WTW site, the proportion of water abstracted from each catchment will vary depending on the licensed amount of water available from each catchment.

The risk to each receptor (the abstraction point in the first instance but ultimately the receiving WTWs) is associated with:

- the possibility of spills at the surface whereby fracking fluids may find their way to the surface watercourse via the surface drainage network;
- where the river course is in direct connection with groundwater there may be pollutants entering the river from contaminated groundwater, although the dilution in the latter case can be significant depending on the time of the year and the flows in the river;
- the presence of upstream wastewater treatment works WWTWs receiving flow-back or production water from exploration and development wells whereby pollutants bypass the treatment process (if inadequate for the nature of the water to be treated) and make their way into the watercourse.

Any pollutant within the surface water catchment that drains to the point along the river where the abstraction takes place could potentially contaminate the drinking water supply. While there are several factors that contribute to the level of exposure of a single surface water abstraction (e.g. travel time to the river, river flow velocity and volumes, volume of spillage, etc.), it is assumed for this assessment that everything within the catchment would pose a risk to the abstraction (i.e. attenuation processes are not considered).

Quantifying the risk associated with the presence of WWTWs upstream of the surface water intake would require identification of the WWTWs that are most likely to be receiving the fracking wastewater for treatment or the locations of bespoke water treatment built to serve the mining (gas extraction) activities.

There are concerns that, while WWTWs facilities would need to be able to adequately cope with the nature of the water quality being treated, some compounds like brominated Disinfection By-Product precursor (DBP) may bypass treatment facilities and be abstracted further downstream, therefore posing a risk to surface water abstraction facilities. Halogens like chloride and bromide are difficult to remove from wastewater and if discharged from WWTWs, they can elevate chloride and bromide concentrations in drinking water sources. Upon chlorination of drinking water, these halogens react with naturally occurring organic matter and form DBP precursor (USEPA, 2012).

Effectively, the risks to surface water abstractions from WWTWs can be controlled and managed by controlling the volumes of wastewater from fracking operations that are discharged through the WWTWs.

Wastewater Treatment Capacity

There will be a need for disposal of wastewaters resulting from fracking operations on wells located in STWL sewage areas.

The SEA for the 14th round identified that flowback (the fracturing fluid injected into the shale rock during hydraulic fracturing which returns to the surface) could range from 3,000 cubic metres to 18,750 cubic metres of water per well. This could mean that up to 108 million cubic metres of wastewater would require treatment. Depending on where the wastewater is treated, the additional volume could place a significant burden on existing wastewater treatment infrastructure capacity and require further or new investment. However, if on-site treatment and recycling could occur, wastewater volumes (and associated vehicle movements) could be reduced.

The United Kingdom Water Industry Research (UKWIR) study (Stone et al, 2013) indicates that only urban areas with populations >50,000 will have large enough WWTWs to process the wastewater. The urban areas that lie within the areas that are of interest to operators for Shale Gas or CBM exploration are most likely to have larger WWTWs. On this basis the WWTWs around the urban conurbations of Sheffield, Chesterfield, Mansfield, Nottingham and Derby are most likely to be at risk from the effects of wastewater treatment from fracking operations as they have sufficiently large treatment capacities. STWL have three WWTWs that serve over >500,000 population.

The United States Environmental Protection Agency (USEPA), (2012) suggests that one of the main issues for WWTWs with fracking wastewater is the high Total Dissolved Solids (TDS) associated with these waters, which can typically have concentrations >45,000 mg/l. Several commercial processes for treating hydraulic fracturing wastewater are mentioned, including crystallization (zero liquid discharge), thermal distillation/evaporation, electrodialysis, reverse osmosis, ion exchange, and coagulation/flocculation followed by settling and/or filtration.

Any WWTW facility accepting wastewater will also have to deal with a concentration of Naturally Occurring Radioactive Material (NORM) (UKWIR, 2013). In fact, NORM may pose difficulties to wastewater treatment works due to the disposal of both liquids and sludge and WWTW facilities are not equipped for treatment of these substances.

Data Processing

To assess the risks identified as part of the conceptual understanding discussed in the previous section, relevant datasets were obtained and processed. This is summarised in the sections below.

GIS software

The risk screening assessment was carried out using a combination of the open source GIS software GRASS (Geographic Resources Analysis Support System) GIS, for processing and QGIS (previously known as Quantum GIS) for visualisation, along with Microsoft Excel for additional processing and tabulation.

GRASS GIS is a free, open source GIS capable of handling raster, topological vector, image processing, and graphic data. QGIS is a cross-platform free and open-source desktop GIS application that provides data viewing, editing, and analysis capabilities.

Sources of data

Various datasets relevant to risk screening have been obtained, including the location and vertical/horizontal proximity of potentially developed areas to groundwater and surface water resources and STWL's assets.

Most of the data formats were readily imported into a GIS, and were ready to use, to allow further analysis in the risk ranking process described in the following section. Where GIS datasets were not readily available, these were digitised from existing reports and georeferenced, requiring significant processing within GIS.

The Coal Authority were approached to obtain their fissure and breakline data to compliment the fault data obtained from the BGS. These data, which were collected following claims made under the Coal Mining Subsidence Act 1991, comprise fissures and breaklines, (typically) faults which have been recorded by the Coal Authority and incorporated into their GIS system. An example of some of the datasets obtained and processed with the GIS are shown on Figure 10.

Data type (source)	Cost (Free or +(low) to +++(high))
PEDL areas (DECC)	Free
UCG licensed areas (Coal Authority)	++
Existing licences for unconventional gas exploration and production (DECC, Landmark Information Group)	Free/+
Proposed licences for unconventional gas exploration and production (Landmark Information Group)	+
Spatial extent of reserves (BGS)	Free
Depth to reserves (BGS)	+++
Faults (BGS, Coal Authority)	Free
Geometry of aquifers (BGS)	+++
Aquifer properties (EA, client, BGS)	+
STWL area (client)	Free (client supplied)
STWL abstractions (client)	Free (client supplied)
STWL Water Resource Zones (client)	Free (client supplied)
STWL WWTWs (client)	Free (client supplied)
SPZs for groundwater (client)	Free (client supplied)
Source criticality (client)	Free (client supplied)
Urban conurbations (Office for National Statistics)	Free
Surface water drainage catchments (client, Flood Estimation Handbook)	Free

Table 2. *A summary of the data obtained for the risk screening.*

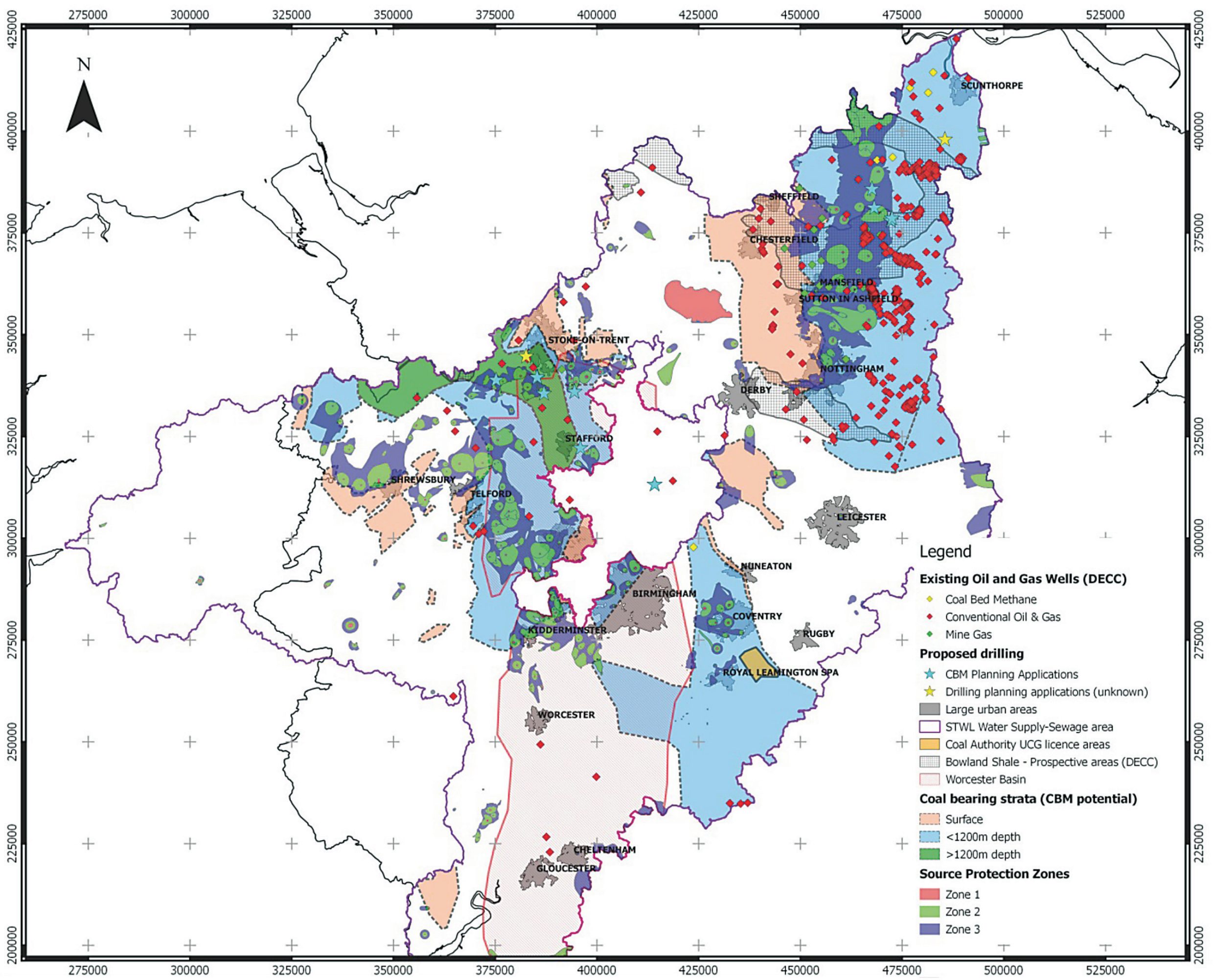

Figure 10. *Map showing key oil and gas development (existing and proposed) data within the STWL area (see Table 2 for data sources).*

Risk Ranking Methodology

The standard approach recommended for environmental risk assessment and management is set out in Guidelines for Environmental Risk Assessment and Management (DEFRA, 2011). This recommends a source-pathway-receptor method. In the context of this screening assessment, these elements may be defined as:

- Source: Areas that, due to the presence of UCOG reserves (e.g. Bowland Shales), are classified as prospective in the short, medium, or long term (14th PEDL round). Effluent from WWTWs can also be considered as a source term if the effluent is then abstracted downstream.
- Pathways: The mechanisms by which the source term is linked to the receptor (STWL assets) and, through this linkage, may impact the receptor. This would include risk factors like the thickness of the separating strata, the presence of faults, existing oil and gas wells and planned wells that lie within abstraction catchments (SPZs for groundwater abstractions and surface water catchments for surface water abstractions).
- Receptors: These are all the STWL assets, including groundwater and surface water abstractions and WWTWs.

In the source-pathway-receptor method, there is no risk when the source-pathway-receptor linkage is broken (i.e. one of source, pathway or receptor is missing). However, in this assessment the persistence of the linkage is maintained (i.e. a risk would still be present) even if a pathway was present but there were no source. The justification for this approach is that the assessment is undertaken on a very small scale and the uncertainties associated with the datasets can be of the order of kilometre. The persistence of the source-pathway-receptor linkage can be removed when the assessment is undertaken at larger scales and the uncertainties in the datasets are reduced.

A preliminary risk ranking methodology has been derived to estimate the risks of UCOG exploration and development to STWL groundwater and surface water sources. The risk factors have been grouped into source terms and those that can be considered pathways.

Risk Ranking for Groundwater Sources

Relevant datasets were imported into GRASS GIS and clipped to the combined STWL water supply and wastewater area. A coded routine using Python script was programmed into the GIS to assign, for each groundwater source, a rating against each range identified for the individual risk factors. The data were then exported from the GIS into a spreadsheet where the risk model was fully implemented by incorporating the weighting factors and deriving the full risk scoring.

Risk Factor	Range	Rating	Risk Factor Weight	Supporting dataset*	Rational for range and rating	Rational for risk factor
Thickness of separating layer between base of aquifer and top of resource (m)	<600	4	0.1	Depth to reserves	<600 highest risk, (Davies et al 2012; arbitrary but equal split to max. depth.	Upward migration of contaminant will be longer for thicker separating layer
	600-1500	3				
	1500-3000	2				
	3000-4500	1				
Waste disposal term	Inside	1	0.05	STWL dataset for WWTWs with population >50,000	-	Inappropriate treatment of effluent from drilling/fracking operations then discharge from WWTWs.
	Outside	0				
13th Round PEDL (areal coverage)	Inside	1	0.20	Current PEDL areas	-	Short to medium term exploration and development will be prioritised in these areas.
	Outside	0				
	Outside	0				
Number of faults within SPZ	>10	3	0.03	Faults	Based on typical number of faults (1:625K scale) intersecting SPZ areas	Faults are considered pathways for the migration of methane, fracking fluids, NORM, and deep groundwater.
	10-2	2				
	1	1				
	0	0				
Existing O&G wells within SPZ (number of wells)	>10	3	0.04	Existing licences for unconventional gas exploration and production	Based on typical number of wells (1:625K scale) intersecting SPZ areas	Included to account for potential casing failures which will increase with the age of the wells.
	10-1	2				
	1	1				
	None	0				

Table 3. *Example of a risk ranking method for groundwater sources using selected risk factors. Not all risk factors identified in the study are shown here. O&G: Oil and gas.*

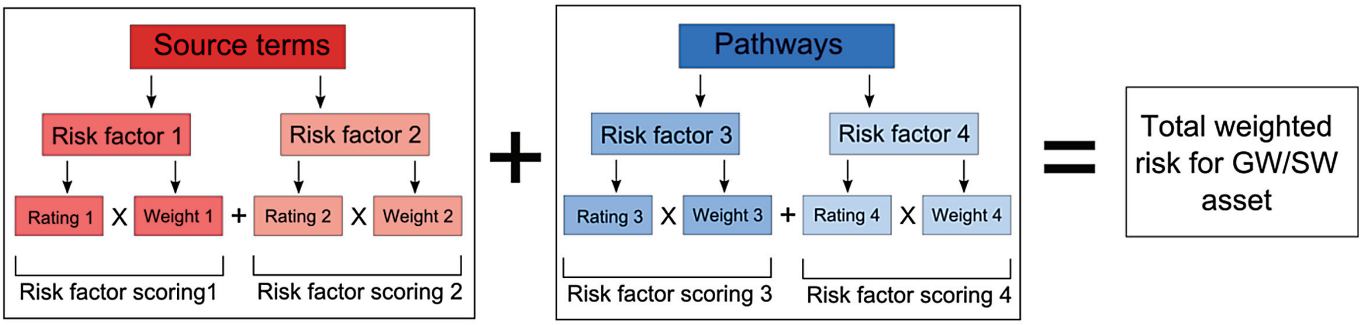

Figure 11. *Schematic of risk screening assessment method. (GW: groundwater, SW: surface water).*

Each risk factor was assigned a weighting. The weightings were set to ensure that the potential proportional contribution of each risk factor to the overall normalised risk was appropriate based on literature and research reviews. The proportional weighted risk was not equal for each risk factor; risk factors of greater significance were given a greater proportional contribution. The scoring of each risk factor was determined by the product of the rating and the relevant weight. The total score for the groundwater source was calculated by summing the individual scores for each risk factor (Figure 12).

The maximum total weighted score theoretically achievable by a groundwater source would be 2.74 (corresponding to maximum risk). Table 4 summarises the total maximum contribution, after normalisation, of each risk factor to the overall risk posed by UCOG to a groundwater source.

Table 4 shows that the weighting factors have been selected so that the contribution of the risk factor to the total normalised risk is proportional to the risk that may be posed by the individual risk factor. The risk to groundwater sources was initially calculated without considering the criticality of the source. A second total normalised weighted score was calculated for the sources where STWL has defined a criticality for the source. The total weight of the source criticality was set to contribute 30% to the newly calculated total normalised weighted score. Separate scores were calculated for Shale Gas, CBM and UCG.

Groundwater sources were grouped into four risk categories based on the total score achieved. The risk bandings have been defined based on the distribution of the normalised total risks and considering that the potential for a source to score a 100% risk is remote as this would imply the source would obtain maximum scores for all risk factors. The risk categories are summarised in Table 4.

Risk term	Type of risk term	Risk factor	Weighted maximum contribution to overall risk
Source	Natural	Prospective area (areal coverage)	9.7%
		13^{th} Round PEDL (areal coverage)	7.7%
		14^{th} Round PEDL (areal coverage)	3.9%
	Anthropogenic	WWTW effluent discharge	5.8%
Pathway	Natural	Thickness of separating layer between base of aquifer and top of resource (m)	15.4%
		Aquifer transmissivity (m^2/d)	7.7%
		Number of faults within SPZ	20.8%
	Anthropogenic	Existing O&G wells within SPZ (number of wells)	27.8%
		Proposed O&G drilling in SPZ (number of wells)	6.9%
		TOTAL	100%

Table 4. *Contribution of each risk factor to the overall normalised risk.*

Risk category	Negligible	Low	Medium	High
Total risk score	0-24.9%	25-34.9%	35-49.9%	50-100%

Table 5. *Risk categories for groundwater sources.*

Risk Ranking for Surface Water Sources

An approach similar to that adopted for the groundwater sources was adopted for the surface water sites, although a reduced number of datasets (risk factors) was used. Whilst it is acknowledged that ignoring some factors leads to a very coarse assessment of the actual risk, a more in depth assessment for surface water was beyond the remit of this study. Risk factors not accounted for in the assessment included:

- the effects from groundwater discharges to surface watercourses;
- the travel time of potential pollutants within the catchment that would be affected by the area of the catchment;
- the volumes abstracted at each abstraction point and the proportions of raw water that these individual abstraction points supply to the respective WTWs;
- the proportion of the surface water catchment occupied by PEDL areas.

Instead of using SPZs as the capture area within which to identify existing/planned oil and gas wells, the derived surface water catchments draining to the STWL surface abstraction points were used.

A separate routine was programmed into GIS to assign, for each abstraction point, a rating against each range for each of the individual risk factors (Table 6).

The total score for the surface water source was calculated by summing the individual scores, similar to that done for the groundwater sources. The maximum total score theoretically achievable by a surface water source would be 2.92 (corresponding to maximum risk). Table 7 summarises the total maximum contribution, after normalisation, of each risk factor to the overall risk posed by UCOG to a surface water source. The table does not

Risk Factor	Range	Rating	Risk Factor Weight	Supporting dataset*	Rational for range and rating	Rational for risk factor
Prospective area (areal coverage)	Inside	1	0.32	Spatial extent of reserves		These areas will be exploited before non-prospective reserves with today's technologies
	Outside	0				
13th Round PEDL (areal coverage)	Inside	1	0.22	Current PEDL areas		Short to medium term exploration and development will be prioritised in these areas.
	Outside	0				
14th Round PEDL (areal coverage)	Inside	1	0.10	Proposed PEDL areas		Medium to long term exploration and development will eventually target these areas too which correspond to the Strategic Environmental Assessments undertaken by DECC in 2014.
	Outside	0				
Potential for wastewater disposal at STWL WWTWs			0.28		Population >50,000 upstream	Effluent disposed upstream of abstraction point
Existing O&G wells within surface water catchment (number of wells)	>10	3	0.06	Existing licences for unconventional gas exploration and production	Based on typical number of wells (1:625K scale) intersecting SPZ areas	Included to account for potential casing failures which will increase with the age of the wells.
	10-1	2				
	1	1				
	None	0				
Proposed oil & gas drilling in surface water catchment (number of wells)	>10	3	0.02	Proposed licences for unconventional gas exploration and production	Based on typical number of wells (1:625K scale) intersecting SPZ areas	Included to account for contamination occurring during drilling operations at surface and below surface
	10-1	2				
	1	1				
	0	0				

Table 6. *Risk ranking method for surface water sources.*

Risk factor	Weighted maximum contribution to overall risk
Prospective area (areal coverage)	11.0%
13th Round PEDL (areal coverage)	7.5%
14th Round PEDL (areal coverage)	3.4%
WWTW effluent discharge	28.8%
Existing O&G wells within SPZ (number of wells)	37.0%
Proposed oil & gas drilling in surface water catchment (number of wells)	12.3%
TOTAL	100%

Table 7. *Contribution of each risk factor to the overall risk.*

consider the contribution of source criticality. When source criticality was considered, a total of 30% contribution to the overall risk was assigned to the criticality alone and the remaining 70% was assigned to the sum of the other factors (Table 7).

Separate scorings were calculated for Shale Gas and CBM. Although scorings for UCG have been obtained, it should be noted that none of the risk factors contribute to the overall risk and therefore the sources that were considered in the assessment have a total risk of zero. Surface water sources were grouped into four risk categories, based on the total scoring achieved. The risk categories and their scoring levels are exactly the same as the groundwater risk categories, shown in Table 5.

Results

The results of the risk screening were presented in both spatial (Figure 12) and tabular form with separate output for groundwater and surface water assets and then for Shale Gas, CBM, and UCG.

Wider Applicability Of The Risk Screening Approach

The key aim of this paper is to demonstrate the potential for risk screening using freely available software and free, or commercially available, data. It is considered that the approach described above is applicable to many source-pathway-receptor situations. The approach will lend itself more to some situations than to others and it is likely to be most useful where there are numerous receptors or numerous sources (e.g. potential impacts on groundwater sources from quarry discharges/spills) and numerous risk factors.

The quality and availability of data is increasing day by day; although, the feasibility of the approach for a specific case will depend on data availability. That said, a relative risk ranking can be carried out relatively quickly and with relatively few data and then refined as more and better quality data become available over time.

Conclusions

The risk screening approach described in this paper has successfully allowed STWL to rank its surface water and groundwater sources with respect to potential for impact from UCOG development in the form of Shale Gas, CBM, and UCG. The resulting ranking does not imply that sources and water supply or treatment is at unacceptable risk of impact but allows advance warning of where issues may need to be resolved and where resources may need to be directed.

With the large size of the area being covered, the large number of potential receptors, the limitation of data availability and quality, and the inherent uncertainties about the future development of UCOG, the assessment is necessarily high level. However, it represents a cost-effective first pass which can be refined as the data improve. In this circumstance the use of GIS is an effective way of dealing with multiple datasets related to sources, pathways, and receptors.

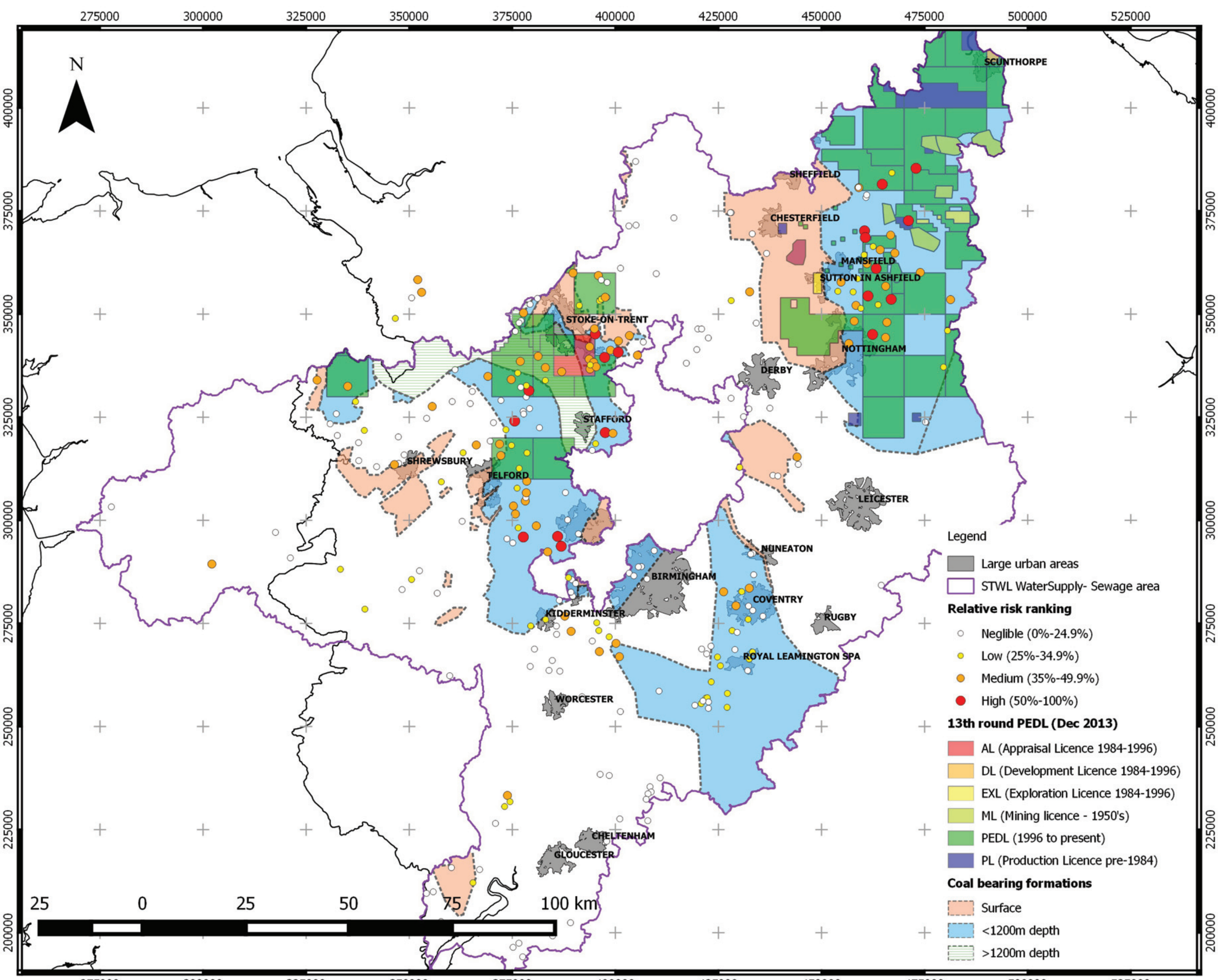

Figure 12. *Example of spatial output of relative risk ranking of STWL assets for UCOG development (in this case CBM development).*

One of the benefits of this approach is that it takes advantage of the increasing number of free datasets that are becoming available and which will continue to do so. Even the QGIS and GRASS GIS software are free to use for commercial purposes. Over time the challenge is becoming less to do with finding funds for data and processing tools but more to do with coming up with innovative ways of applying, processing, and presenting the data that are available.

Similar risk screening approaches could therefore be used for other sites or types of operation, such as quarries, with the selection of the appropriate datasets. This could include assessment of risks both to and from the operation.

Whilst there is great potential for use, the potential for misuse is also there. Despite the availability of data, the approach still relies on a good conceptual understanding, the appropriate processing methodology and a proficiency in the use of the tools – in this case GIS and Python programming.

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